# A Simple Technique For Estimation of Reservoir Permeability Which Includes The Absorption Effect of Synthetic Seismic Reflection Data

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***Abstract***

*Relationships among elastic parameters and rock properties, and ultimate reservoir parameters have been established in continuum mechanics and rock physics. Therefore, it should be possible to estimate reservoir permeability from the seismic data. We used Sismanto's method based on Biot's solution of wave equation in an elastic porous medium and the approximations of Turgut-Yamamoto to allow an establishment of a linear relationship between attenuation coefficient or amplitude ratio as a function of the inverse of the square of frequency. The slope of this function includes the permeability. It can be shown that this technique agrees to the measurement of the permeability of a porous medium from seismic waveforms. We examined this technique to estimate the reservoir permeability by using synthetic seismogram data. The result show that has an error less than 5 %, it means that the study of permeability estimation from surface seismic data is possible by using an accurate calibration step.*

***Keywords:*** *Seismic wave, permeability, Biot, Turgut-Yamamoto.*

## Introduction

Reservoir characterization is one of the advanced steps in seismic exploration to identify physical properties of a reservoir such as thickness, porosity, permeability, density, compressibility, and water saturation. These physical properties are used to model the fluid flow in a producing field. Recent new geophysical methods for example, AVO and tomography, generally attempt to directly estimate the reservoir physical properties from the seismic data. Turgut and Yamamoto (1988) developed a one-dimensional (1D) model of VSP, which includes mode conversion through slow compresional waves as an energy loss mechanism based on Ganley (1981). Horizontal and vertical seismic profiling synthetic seismograms which include the absorption effect of the reservoir, especially for permeability, has been constructed by Sismanto, *et.al.* (2003a). The Sismanto's technique is to combine the Turgut-Yamamoto and Ganley mechanism. Turgut and Yamamoto (1988; 1990) explored the possibility of predicting porosity and permeability of marine sediment by analyzing phase velocity dispersion and attenuation of the fast compressional waves as a function of frequency. Meanwhile, most theoretical and experimental researches prove that there is a close relationship among waves, elastics, and reservoir parameters. This relationship also agrees with the field data (Munadi, 1998; Saar and Manga, 1999). Thus, the reservoir parameters are believed to affect seismic wave characters. With this point of view, reservoir parameters, such as porosity and permeability should therefore, are able to be theoretically obtained from the seismic data.

Sismanto, *et. al* (2003b) developed a technique to estimate the permeability on the seismogram synthetic based on Turgut-Yamamoto equation, but the relationship of the permeability estimation to the permeability model is still multifaceted. Furthermore, Sismanto *et. al,* (2005a) published a simple technique to estimate the permeability on the real 3D seismic data based on Turgut-Yamamoto equation as well. The Turgut-Yamamoto equation was modified to expand a linear relationship between the attenuation coefficient and the amplitude ratio as a function of frequency, but there are still many problems were ignore.

The aim of this paper is to examine the Sismanto *et. al,* (2005a)'s method to estimate reservoir permeability from the synthetic seismic reflection data. Consequently, we can minimize the real problem in order to get the accuracy of the technique.

**Fundamental**

Two basic equations describing the relationship between dilatational and shear waves in a fluid-saturated porous (uncon-solidated) isotropic and elastic media such as marine sediments, are (Biot, 1956)

$$\mu\nabla^2\vec{u} + (\overline{H}-\mu)\nabla\theta - C\nabla\varsigma_p = \rho\frac{\partial^2\vec{u}}{\partial t^2} - \rho_f\frac{\partial^2\vec{V}}{\partial t^2} \quad (1)$$

$$C\nabla\theta - M\nabla\varsigma_p = \rho_f\frac{\partial^2\vec{u}}{\partial t^2} - m\frac{\partial^2\vec{V}}{\partial t^2} - \frac{\eta}{k_p}\frac{\partial\vec{V}}{\partial t} \quad (2)$$

in which $\vec{u}$ is the frame displacement vector, $\vec{V}$ is the seepage displacement vector, $\theta = \text{div}\,\vec{u}$, $\varsigma_p = \text{div}\,\vec{V}$, $\rho$ is the bulk density $[\rho = (1-\phi)\,\rho_r + \phi\,\rho_f]$, $\rho_r$ is the density of grain, $\rho_f$ is the density of fluid, $\phi$ is the porosity, $\eta$ is the viscosity of fluid, and $k_p$ is the coefficient of the permeability. $\overline{H}$, $C$, and $M$ are the Biot's elastic moduli, $\mu$ is the shear modulus, and $m$ is the virtual mass expressed as $m = \alpha\,\rho_f/\phi$, with $\alpha = 1.25$ (Turgut and Yamamoto, 1990). The Biot's elastic modulus are expressed by the following relations

$$\overline{H} = \frac{(K_r - K_b)^2}{(D_r - K_b)} + K_b + \tfrac{4}{3}\mu,$$

$$C = \frac{K_r(K_r - K_b)}{D_r - K_b},\ M = \frac{K_r^2}{D_r - K_b}, \text{ and}$$

$$D_r = K_r\left[1 + \phi\left(\frac{K_r}{K_f} - 1\right)\right] \quad (3)$$

where $K_r$ is the bulk modulus of the grain, $K_f$ is the bulk modulus of the fluid in the pores, and $K_b$ is the bulk modulus of the skeletal frame. According to Turgut and Yamamoto (1990), the bulk modulus of skeletal frame $K_b$ and the porosity are related to the shear modulus as

$$K_b = \left(\frac{2\sigma}{1-2\sigma} + \tfrac{2}{3}\right)\mu, \text{ and}$$

$$\phi = \frac{K_f(K_r - -K)}{(K_r - K_f)(K - K_b)} \quad (4)$$

where the shear modulus $\mu$, the Poisson's ratio $\sigma$ and the bulk modulus $K$ are estimated from the velocities of the P and S waves, where their relationships are given by

$$\mu = \rho V_s^2,\ \sigma = \frac{3K - 2\mu}{2(3K+\mu)}, \text{ and}$$

$$K = \rho\left(V_p^2 - \frac{4}{3}V_s^2\right) \quad (5)$$

**3. Methods**

To estimate the permeability, we need a seismic waveform velocity and its spectral analysis of the events. The bulk modulus of grain $K_r$, the density $\rho$ and the bulk modulus of fluid $K_f$ have to be defined previously. According to Turgut-Yamamoto (1990) approximation and Geertsma and Smit (1961) indication for marine sediment with high $Q$ Eqs. (1) and (2) can be obtained in the following form,

$$Q^{-1} \approx \frac{(V_\infty^2/V_o^2) - 1}{\frac{q_i}{A} + \frac{A}{q_i}\cdot(V_\infty^2/V_o^2)} \quad (6)$$

where $q_i = \eta/k_p\omega$ is the imaginary part of $\hat{q}$, and $A = (\rho m - \rho_f^2)/\rho$. Whereas,

$$V_o^2 = \overline{H}/\rho \text{ for } \omega \to 0, \text{ and} \quad (7)$$

$$V_\infty^2 = (Hm + M\rho - 2C\rho_f)/\rho m - \rho_f^2 \text{ for } \omega \to \infty$$

Then, it can be found the location of the relaxation frequency (maximum attenuation) in a ($Q^{-1}$- $f$) curve as

$$f_r = \left[\frac{\rho\,\eta}{2\pi\left(\rho\, m - \rho_f^2\right)\cdot k_p}\right]\frac{V_0}{V_\infty} \tag{8}$$

By using the relaxation frequency, the permeability coefficient can be estimated, if the other parameters have been determined. However, it is rather difficult to get a good curve of $(Q^{-1}\text{-}f)$ relationship for real data. Sismanto, *et al.*, (2005a) modified the relationship of $(Q^{-1}\text{-}f)$ into a linear form.

Eq. (6) can be rewritten as

$$Q = \frac{\dfrac{q_i}{A} + \dfrac{A}{q_i}.W}{W - 1}, \tag{9}$$

where $W = V_\infty^2 / V_0^2$. According to the spec-tral ratio method for estimating $Q$ in laboratory, the definition of the quality factor $Q$ is,

$$Q = \frac{\omega}{2V_p\alpha(\omega)}. \tag{10}$$

By combining Eqs. (9) and (10), ones obtains

$$\frac{x2V_p}{\omega^2(W-1)} + \frac{W\,2V_p}{x(W-1)} = \frac{1}{\alpha(\omega)} \tag{11}$$

in which $x = \eta\rho/(k_p(\rho m - \rho_f^2))$. The relation-ship of $\alpha(\omega)$ and the frequency in Eq. (11) is asymptotic for high frequency region (ω>>). Unfortunately, we are not interested in the high frequency region and in practice it is difficult to obtain the asymptotic value because the frequency content of the seismic data is less then 200 Hz. While, the relationship between $[1/\omega^2]$ and $[1/\alpha(\omega)]$ is linear for all frequency. However, the linear relationship of the data just takes place only in the frequency content of the signal.

From the slope $\gamma$, we can estimate the permeability, i.e.,

$$k_p = \frac{2V_p\eta\rho}{\gamma.\left(\rho m - \rho_f^2\right)}(W-1)^{-1}. \tag{12}$$

It is obvious that the coefficient of attenuation $\alpha(\omega)$ can be calculated from the spectral ratio method by

$$\alpha(\omega) = \ln\left(\frac{A_n(\omega)}{A_1(\omega)}\right).d^{-1}, \tag{13}$$

where $A_n$ and $A_1$ are the amplitude of signal at the $n$ and $1$ positions in the frequency domain respectively. In vertical seismic measurement (VSP), $d$ is the distance between receivers in positions $1$ and $n$. In the reflection measurement $d$ is the path difference of the recorded seismic wave at the surface.

Substituting Eq.(13) into Eq.(11), we will obtain

$$\frac{2V_p}{d(W-1)}\left(\frac{x}{\omega^2} + \frac{W}{x}\right) = \left[\ln\left(\frac{A_n(\omega)}{A_1(\omega)}\right)\right]^{-1}. \tag{14}$$

The curve of Eq. (14) is asymptotic for high frequency (ω>>) and linier between $(1/\omega^2)$ and (1/ amplitude ratio in logarithmic). If the slope is $\tau$, we can determine the permeability of the medium, i.e.,

$$k_p = \frac{2V_p\eta\rho}{d\,\tau\left(\rho m - \rho_f^2\right)(W-1)}. \tag{15}$$

The forms of Eq.(14) and Eq.(11) are similar. The main difference is in the data. Eq. (11) needs more good seismic traces to calculate the attenuation coefficient, but using Eq. (14) we need only at least two traces of seismic data in CDP gather.

## 4. Synthetic seismograms

Sismanto, *et. al.* (2003a) associated the effect of absorption and dispersion according to Ganley (1981) with dispersion and attenuation. The attenuation effects are calculated from the wave number of Biot's equation. The theoretical seismograms are based on Ganley(1981)'s method. The dispersion effect comes from the reflectivity as a function of frequency. For the absorption calculation, Futterman(1962)'s absorption-dispersion equations, are realized.

Therefore, the synthetic seismograms cover reservoir parameters, elastic parameter and wave parameters. The permeability of the model depends on those parameters is given by Geertsma and Smit (1961),

$$k_p = \frac{\phi\eta}{2\pi\rho\, f}\left[\frac{V_\infty^4 - V_p^2 V_\infty^2}{V_p^2 V_o^2 - V_o^4}\right]^{-\frac{1}{2}} \qquad (16)$$

The relationship of the permeability to the velocity and frequency for sandstone is illustrated in Fig. 1 and Fig. 2, respectively. Those figures show that for higher frequency the velocity dependency is not so significant relative to the permeability. Otherwise, the permeability is strongly influenced by the frequency. The relationship of dependency among frequency, velocity, and permeability has been discussed theoretically by Sismanto *et al.* (2005b).

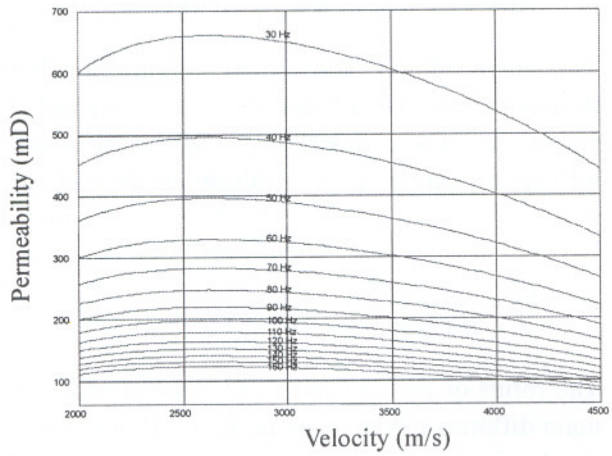


**Fig.1.** The relationship of the permeability to the velocity for sandstone type. It is shown that for higher frequency the velocity dependency is not so significant relative to the permeability.

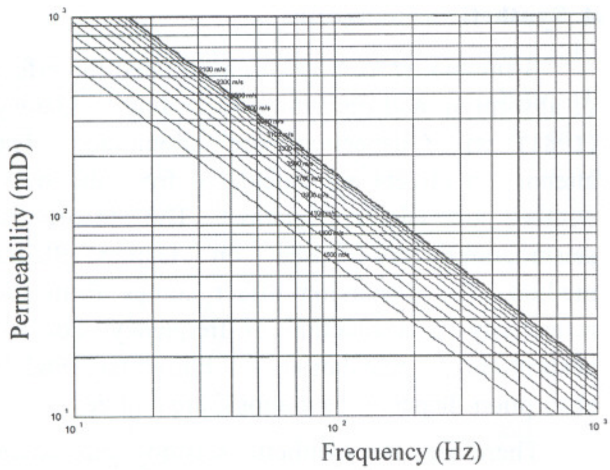


**Fig.2.** The relationship of the permeability to the frequency for sandstone type. This relationship shows that the permeability is strongly influenced by frequency.

The basic rock properties of marine sediment are based on Turgut and Yamamoto (1990). The kinematics viscosity of pure fluid $\eta$ *is* 1.0 x $10^{-6}$ $m^2/s$, the bulk modulus of fluid $K_f$ is 2.3 x $10^9$ $N/m^2$, the bulk modulus of grain $K_r$ is 3.6 x $10^{10}$ $N/m^2$, the density of fluid $\rho_f$ is 1.0 x $10^3$ $kg/m^3$, and the density of grain $\rho_r$ is 2.65 x $10^3$ $kg/m^3$. While, velocity of the P wave $V_p$ is obtained from the seismic data, and the S wave velocity $V_s$ and the density $\rho$ are estimated by empirical equations (Mavko, *et.al,* 1998). Then, the bulk modulus of the skeletal frame and the porosity are estimated by Eqs.(4), Biot's elasticity parameters are determined by Eq.(3), and the velocity of the zero and the high frequency range are calculated by Eq.(7).

## 5. Examples of Numerical Result

Synthetic seismograms of poro-elastic waves in two layer models of seismic reflection are shown in Fig. 3. The model uses a velocity $V_{p1}$ of 3000 m/s (sandstone) over the limestone with $V_{p2}$ of 4000 m/s. The Ricker wavelet frequency is 70 Hz. Fig. 4 is the frequency spectrum of the synthetic seismogram events of Fig. 3. The spectrum shows that there is some frequency-shift and amplitude attenuation, especially in (10-70) Hz. The frequency content is affected by the attenuation system of the medium. The two-layer model uses the thickness of first layer of 150 m and receiver interval of 20 m. Then, the other physical properties can be obtained such as the shear wave velocity $V_{s1}$ and $V_{s2}$, which are 1594 m/s and 2157 m/s, the density $\rho_1$ and $\rho_2$ are 2.19 $.10^3$ $kg/m^3$ and 2.33 $.10^3$ $kg/m^3$, the porosity $\phi_1$ and $\phi_2$ are 56 % and 17 %, and the permeability $k_{p1}$ and $k_{p2}$ are 278 mD and 209 mD, respectively. Those physical properties are enforced to construct the synthetic seismogram of the two-layer model, which is shown in Fig. 3. The permeability value of the synthetic seismogram, which is calculated from Eq.(16), is implemented as a reference.

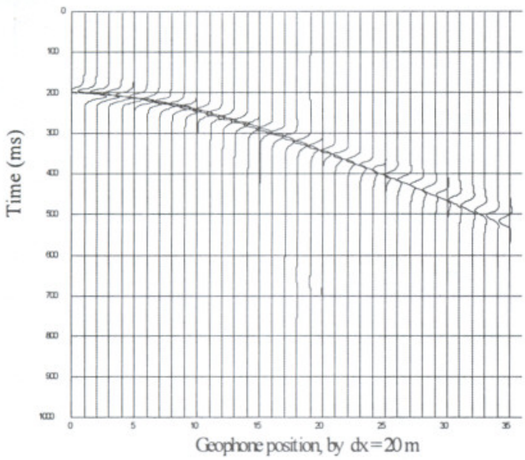


Fig. 3. Synthetic seismograms of poro-elastic waves in two layer models of seismic reflection. The model uses a velocity $V_{p1}$ of 3000 m/s (sandstone, 150 m) over the limestone $V_{p2}$ of 4000 m/s, using Ricker wavelet frequency of 70 Hz.

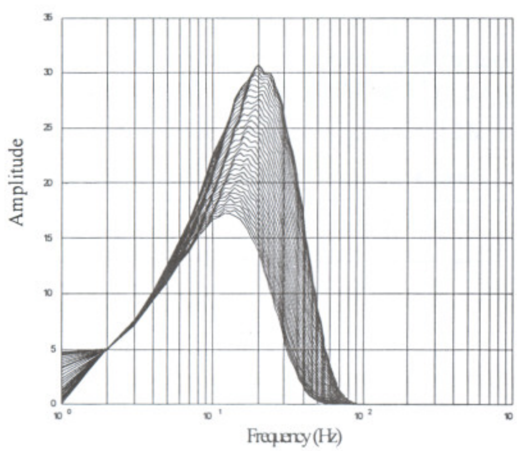


**Fig. 4.** Frequency spectrum of Fig. 3. There are some frequency-shift and amplitude attenuation, especially in the (10-70) Hz. The frequency content is affected by the attenuation system of the medium.

Some two-layer models are constructed with the $V_{p1}$ velocity of sandstone as first layer; of 3000 m/s and the thickness is 150 m over the limestone in which the velocity is 4000 m/s. The synthetic seismograms use several frequencies, and several velocity variations. When the velocity is put to be constant, the frequency is varied and vice versa. The permeability inversion of the two-layer model by the linear method is compared to the reference permeability; it gives equivalence function for several velocities and various frequencies. The scale factor of calibration is obtained from those curves. The scale factors are not unique, but are as a function of velocity. In this case we divide them into 4 groups of scale factor in the same range value of permeability i.e., (3350-3800) m/s, (2950-3350) m/s, (2450-2950) m/s, and (2000-2450 m/s) intervals as presented in Fig. 5a and 5b. There is a linear correlation between the permeability of the model and the permeability from estimation. The linear function of this relation is called the scale factor of the calibration.

The inversion method is applied to estimate the permeability based on the known velocity of the model on the synthetic seismogram, and the results are given in Fig. 6 for constant frequency and varying velocity and Fig. 7 for constant velocity and varying frequency. The shape of curves in Figs 6 and 7 are similar to the theoretical curve in Figs. 1 and 2, formulated by Geertsma and Smit (1961). It means that the synthetic seismogram keeps the permeability information of the model and the inversion method is able to extract it from the (synthetic) seismograms. In the permeability estimation, the average errors for both linear methods are less than 5 %. The errors come from determination of the linear area in the curve. However, the permeability estimation with surface seismic data is basically possible but requires precise calibration.

## 6. Conclusions

The permeability of a porous medium has a significant effect on the frequency depen-dence of the attenuation even in the low frequency range relevant for surface seismic. For testing in synthetic seismograms with acceptable approxima-tions a linear relation-ship between the absorption coefficient and the inverse square of the frequency has an error less than 5%. However, a key result of the study suggests that permeability estimation with surface seismic data is possible through it requires accurate calibration.

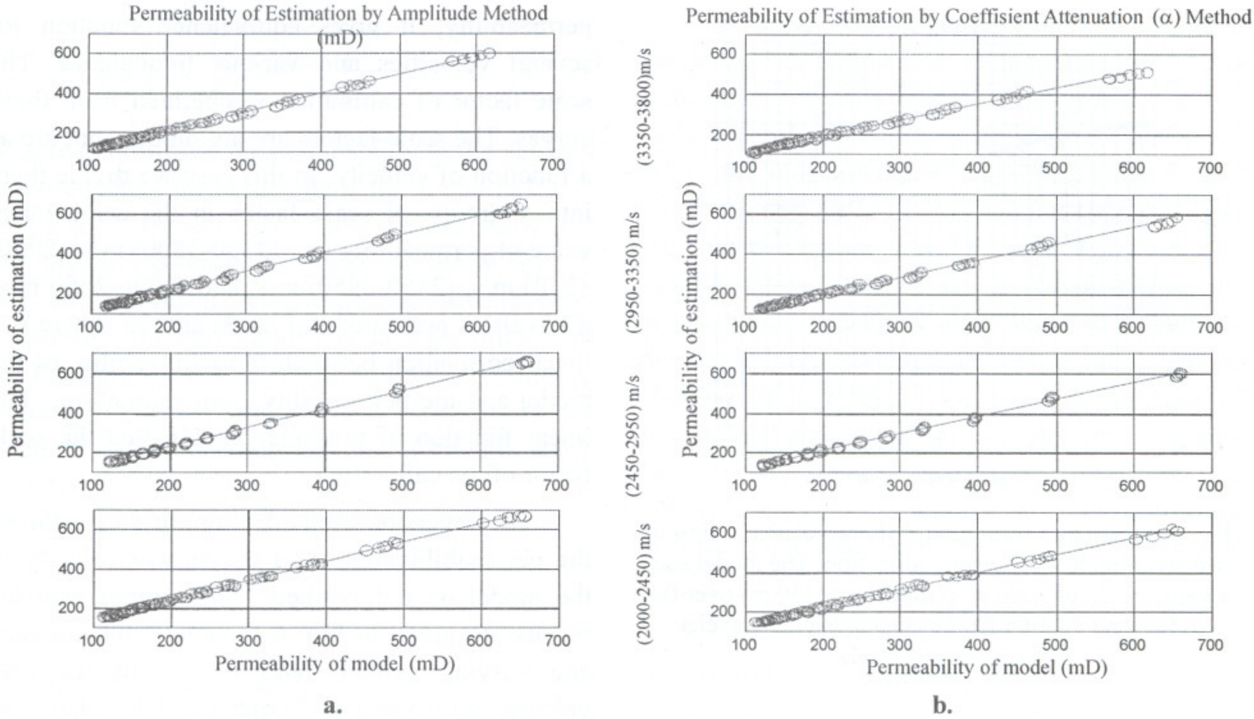


**Fig.** 5a and b. Curve of permeability of estimation versus permeability of model. It is shown that the equivalence factors are not constant, but they are as a function of velocity. We divide the velocity into 4 groups of equivalence factor in the same range value of permeability i.e., (3350-3800) m/s, (2950-3350) m/s, (2450-2950) m/s, and (2000-2450) m/s intervals.

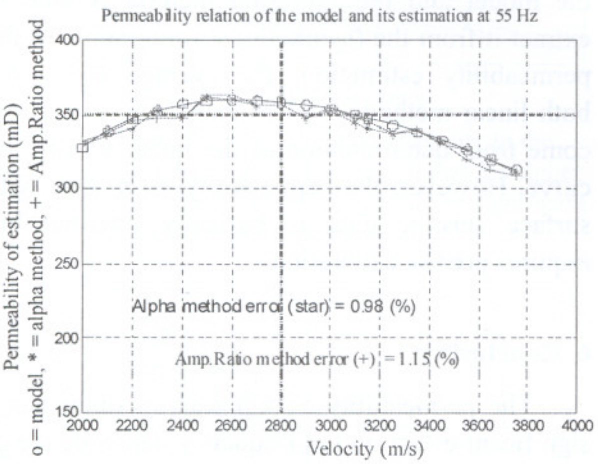


**Fig. 6.** The permeability estimation curves (* is the alpha method, + is the amplitude ratio method) and the model permeability (o) with constant frequency are shown as curvature lines. Each has about 1 % average errors.

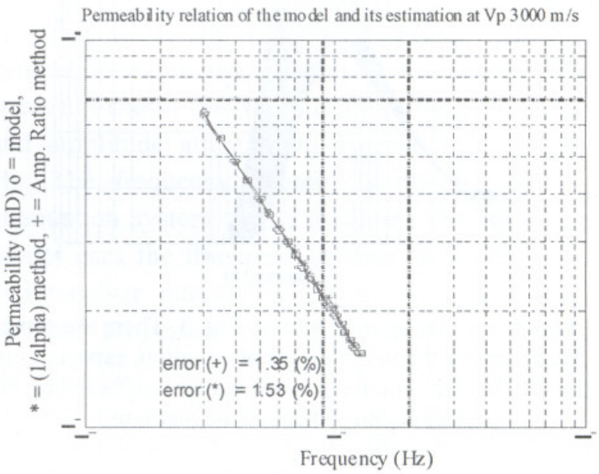


**Fig. 7.** The permeability estimation curve (* is alpha method, + is amplitude ratio method) and the model permeability (o) with constant velocity are shown as linear lines. Each has about 1.5 % average errors.

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